UNIVERSITY OF BIRMINGHAM

University of Birmingham Research at Birmingham

Towards a standardised metadata protocol for urban meteorological networks

Muller, Catherine L.; Chapman, Lee; Grimmond, C.s.b.; Young, Duick T.; Cai, Xiaoming

DOI:
10.1175/BAMS-D-12-00096.1

License:
None: All rights reserved

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):
Muller, CL, Chapman, L, Grimmond, CSB, Young, DT & Cai, X 2013, 'Towards a standardised metadata protocol for urban meteorological networks', *Bulletin of the American Meteorological Society*, vol. 94, pp. 1161-1185. https://doi.org/10.1175/BAMS-D-12-00096.1

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
© Copyright 2013 American Meteorological Society (AMS). Permission to use figures, tables, and brief excerpts from this work in scientific and educational works is hereby granted provided that the source is acknowledged. Any use of material in this work that is determined to be “fair use” under Section 107 of the U.S. Copyright Act September 2010 Page 2 or that satisfies the conditions specified in Section 108 of the U.S. Copyright Act (17 USC §108, as revised by P.L. 94-553) does not require the AMS’s permission. Republication, systematic reproduction, posting in electronic form, such as on a web site or in a searchable database, or other uses of this material, except as exempted by the above statement, requires written permission or a license from the AMS. Additional details are provided in the AMS Copyright Policy, available on the AMS Web site located at (http://www.ametsoc.org/) or from the AMS at 617-227-2425 or copyrights@ametsoc.org.

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

•Users may freely distribute the URL that is used to identify this publication.
•Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
•User may use extracts from the document in line with the concept of ‘fair dealing’ under the Copyright, Designs and Patents Act 1988 (?)
•Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 04. May. 2023

TOWARD A STANDARDIZED METADATA PROTOCOL FOR URBAN METEOROLOGICAL NETWORKS

BY CATHERINE L. MULLER, LEE CHAPMAN, C.S.B. GRIMMOND, DUICK T. YOUNG, AND XIAO-MING CAI

Bringing together the disparate guidelines for best practices in observing and documenting urban stations and existing meteorological networks should improve the quality and applicability of the increasing amount of data gathered by high-resolution urban networks.

The complexity of urban atmospheric processes makes them impossible to measure adequately using traditional surface observation approaches consisting of a few individual monitoring stations. However, in recent years, meteorological observations have benefited from automated monitoring, advancement of sensor technologies (e.g., miniaturization, wider range of sensor types), lower cost of sensors, and improved data transmission to near-real-time communications networks. Once combined, these have enabled the creation of urban meteorological networks (UMNs) with the capability to operate at a range of atmospheric scales (Table 1). Hence, a UMN can be defined as cooperative, spatially distributed meteorological monitoring equipment across an urban environment with autonomous,

TABLE 1. Relations between spatial scales and UMNs, from largest to smallest areal extent [from Muller et al. (2013), with modifications].

Spatial scale[a]	Areal extent (m)	Atmospheric scale (Orlanski 1975)	Description
Regional/ mesoscale	10^4–10^6	Meso-α	Regional mesoscale conditions in the urban, peri-urban, and surrounding rural areas. Mesoscale phenomena may be hazardous and undetected without densely spaced or dynamic monitoring.
Urban/ city scale[b]	10^4–10^5 [b]	Meso-β	Whole city or urban area—dense array of sensors required because of the complex morphology of urban areas.
Neighborhood/ local scale	10^2–10^4	Meso-γ	Minor landscape features (parks, ponds, small topographic features) and neighborhoods with similar types of urban development (surface cover, size, and spacing of buildings, and activity), e.g., city center, old dense residential, or industrial zone.
Microscale	$\leq 10^2$	Micro-γ Micro-β Micro-α	Horizontal and vertical variability cause large differences over small distances. Influenced by dimensions of component elements, e.g., buildings, trees, roads, streets, blocks, courtyards, and gardens. Processes such as turbulence, radiation, and thermal heating are very irregular at these scales; numerous sensors required to represent the processes.

[a] Networks contain individual sensors collecting measurements that can be representative of the mesoscale, local scale, or microscale.

[b] Scale added for the purpose of defining urban networks, since many networks are smaller than mesoscale networks but larger than local-scale networks, covering just the urban areas—spatial scale wide ranging, as it depends on size of city.

near-real-time communication capabilities for transmitting data. The specific scale and type of UMN implemented is dependent upon required coverage, the variables observed, and the atmospheric processes being studied, which, along with resource availability, have an impact on the communications system, physical arrangement of sensors, power sources, size, and topology of the network [see Muller et al. (2013) for a detailed review of such networks]. These advances allow urban environments to be monitored at much finer spatial scales over a wider range of temporal scales than was previously possible, furthering our understanding of atmospheric processes and the impacts of climatic changes. As such, this high-resolution information can help to improve decision making, emergency preparation, weather forecasting, urban climate research, and urban planning for critical infrastructure needs (Chapman et al. 2013).

Because of the growing usage of urban meteorological data, it is imperative that UMNs are implemented and managed to a high standard, using common guidelines where possible. However, existing guidelines and recommendations are for synoptic-scale national networks or for individual urban monitoring stations (e.g., Oke 2004, 2006a; WMO 2008), rather than for UMNs. The divergent requirements, implementation, and management of UMNs suggest that there is an equivalent need for recommendations or standards for UMNs. This would benefit developers and data users by increasing confidence in data representativeness and quality. Indeed, technical information about UMNs is frequently difficult to ascertain because of insufficient reporting and documentation of methodologies and procedures. As data quality may therefore be questionable (NRC 2012; Muller et al. 2013), it makes the ability to cross reference networks difficult. For example, the need to standardize approaches has been identified as critical from the Word Climate Conference-3 (WCC-3, in 2009) for urban areas (Grimmond et al. 2010) and in the United States (NRC 2009, 3–4):

> The status of US surface meteorological observations capabilities is energetic and chaotic, driven mainly by local needs without adequate coordination. . . An over-arching national strategy is needed to integrate disparate systems. . . . Increased coordination amongst existing surface networks would provide a significant step forward and would serve to achieve improved quality checking, more complete metadata, increased access to observations, and broader usage of data serving multiple locally driven needs.

Similarly, the NRC (2012, p. 94) report on urban meteorology prioritizes the need for "regularly updated metadata of the urban observations using standardised urban protocols" as a key short-term need for the advancement of urban meteorology. Furthermore, they note that the value of observational data is maximized only when accompanied by comprehensive metadata, including information on site selection, quality assurance, and management procedures, which are often lacking for urban sites and networks.

Frequently, urban meteorological studies have been critiqued because of poor metadata and/or siting (e.g., Grimmond and Oke 1999; Roth 2000). Most recently Stewart's (2011) review of urban heat island (UHI) studies found a large number failed to adequately describe experimental design, choice of sites, exposure of instruments, and contained a lack of sufficient instrument metadata. To ensure high-quality usage of the data for applications and urban research, recommendations and guidelines must be followed and adequate information reported.

ESTABLISHED GUIDELINES AND RECOMMENDATIONS. The term *metadata* is commonly used for any scheme of resource description for any type of object, digital or nondigital (NISO 2004). It provides the key aspect in any protocol and is essential to effective integration of diverse data sources (NRC 2009). The importance of documenting detailed metadata is highlighted in the Global Climate Observing System (GCOS) climate monitoring principles document (WMO 2003), which states that metadata should be "treated with the same

AFFILIATIONS: Muller, Chapman, Young, and Cai—School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, United Kingdom; Grimmond*—King's College London, London, United Kingdom
***CURRENT AFFILIATION:** Department of Meteorology, University of Reading, Earley Gate, Reading, United Kingdom
CORRESPONDING AUTHOR: Lee Chapman, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom
E-mail: l.chapman@bham.ac.uk

The abstract for this article can be found in this issue, following the table of contents.
DOI:10.1175/BAMS-D-12-00096.1

A supplement to this article is available online (10.1175/BAMS-D-12-00096.2)

In final form 19 December 2012
©2013 American Meteorological Society

FIG. 1. Two very different meteorological stations in terms of siting (e.g., height of sensor, surface cover, distance from obstacles), instrumentation (e.g., type, performance characteristics), and exposure (representativeness would need to be assessed via micro- and local-scale surveys; see main text and supplementary material at http://dx.doi.org/10.1175/BAMS-D-12-00096.2). Both are located within the city boundaries of Birmingham, United Kingdom: (a) a city-center site and (b) an urban park site.

care as the data themselves." Metadata ensure that the end user has "has no doubt about the conditions in which data have been recorded, gathered and transmitted" (Aguilar et al. 2003, p. 2) in order to ensure accurate interpretation, manipulation, and evaluation of results with minimal assumptions regarding data quality or homogeneity (WMO 2008). If detailed metadata are collected, then data can be interpreted accurately, and anomalies or patterns adequately explained and accounted for, whereas if insufficient metadata are collected, then it is difficult or impossible to assess site representativeness and therefore perform reliable data analyses (Stewart 2011). Hence, for meteorological datasets (from in situ monitoring equipment or networks), this includes all supplementary information, characteristics, and descriptions of the monitoring equipment (*instrument*, *sensor*, and *variable metadata*), the monitoring site itself (*site, station,* and *enclosure metadata*), the network (*network* or *subnetwork metadata*), and the network management procedures and communications methods (*cyberinfrastructure* or *network operations metadata*). For example, Fig. 1 shows two different meteorological stations, both located within the same city—detailed metadata are clearly essential for data interpretation at these very different locations.

Existing World Meteorological Organization (WMO) guidelines for the measurement of meteorological variables and climatological practices (e.g., WMO 2008, 2011) are mainly concerned with national and/or global instrument networks whose objective is to collect regionally representative data (i.e., not within urban areas). These standard guidelines contain essential and detailed information relevant to making meteorological observations, including details on requirements for each variable, siting and exposure, instrument calibrations, operating practices, data management and quality assurance/quality control (QA/QC) techniques. However, it is difficult and often inappropriate to conform to standard WMO guidelines when siting equipment in cities, since there are numerous obstructions to airflow and radiation

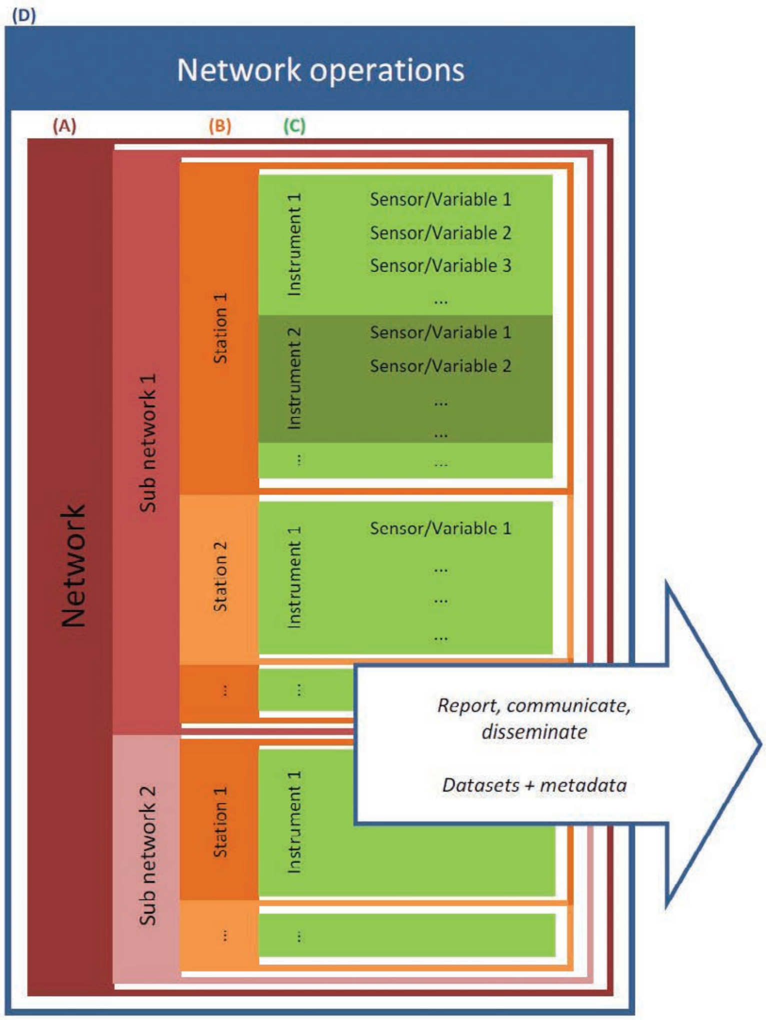

Fig. 2. Schematic of the urban climatological network metadata protocol components—a summary of the metadata elements required for each individual component [(a)–(d)] corresponding to Table 2 (Note: colors correspond to the metadata tables). Please refer to main text for more information.

exchange caused by anthropogenic surfaces, objects, and activities (Oke 2004).

Oke (2006b, 2009) was among the first to call for common urban climate protocols (particularly paying attention to issues related to scales, experimental design, site classification, instrument exposure, and metadata collection), suggesting it would be valuable to have a "manual" for workers in urban climate to aid with the design of observational networks (Oke 2006b). Specific recommendations do exist for siting and exposure of equipment in urban areas (e.g., Aguilar et al. 2003; Manfredi et al. 2005; NOAA 2004; Oke 2006a; WMO 2008, 2011) and outline the type of information that needs to be included as *urban station metadata* in order to obtain representative measurements (e.g., Oke 2004, 2006a,b; WMO 2008).

Within these guidelines and others (e.g., Aguilar et al. 2003; NOAA 2004; Manfredi et al. 2005), specific concepts, definitions, approaches, and recommendations relevant to urban stations are discussed. Furthermore, these guidelines also provide general recommendations for collecting and documenting additional *instrumentation*, *network*, and *operations* metadata that are not intrinsic to a particular station but are equally important (Grimmond 2006; WMO 2011). These additional metadata are essential for anyone utilizing network data, comparing data from different networks, or setting up a new network. For example, Aguilar et al. (2003) and WMO (2011) include comprehensive recommendations for *instrument metadata*, including sensor type, manufacturer, serial number, method of measurement and observation, units, resolution, accuracy, response time, time constant, time resolution, date of installation, corrections and calibrations, and comparison results. These guidelines also call for information on *operational procedures*, such as data processing methods and algorithms, resolution, input source, parameter values, QA/QC, constants, storage procedures, access and processing methods, and communications and transmission methods. McGuirk and May (2003) include similar recommendations but further distinguish between station and network metadata (comprising instrument, research, software, and network procedures). However, such recommendations are often specific to the application (e.g., road weather monitoring, large-scale measurement networks and facilities, individual sites), meaning that certain aspects that are important for UMNs (as discussed in the "Proposed UMN protocol" section) are lacking in these guidelines.

Although metadata and technical information are difficult to ascertain for many established UMNs, there are some for which the complete technical details of their network and the protocols employed have been documented [e.g., Oklahoma City Micronet (Basara et al. 2010); Oklahoma Mesonet (Brock et al. 1995; Shafer et al. 2000; McPherson et al. 2007); West

Texas Mesonet (Schroeder et al. 2005); Helsinki Testbed (Poutiainen et al. 2006)]. As such, these may also be used as a source of guidance for implementing other UMNs. For example, technical information for both the Oklahoma Mesonet and the Oklahoma City Micronet is published and available online. These include information about the station and network architecture and design, site selection and classifications, sensors (including type, accuracy, etc.), sensor locations, communication infrastructure, instrumentation, monitoring, and network operations (e.g., QA/QC, calibration, and maintenance procedures). Additionally, Basara et al. (2010) and Schroeder et al. (2010) outline the land classification procedures used for the Oklahoma Micronet. However, as acknowledged by the NRC (2009), such a level of technical information is very disparate for the majority of UMNs.

By reviewing these existing guidelines, collating recommendations and best practices and establishing where information is missing, this paper endeavors to produce a comprehensive, standardized protocol for assisting those involved in implementing and/or utilizing UMNs.

PROPOSED UMN PROTOCOL. Metadata are required to cover the instrumentation, site, network, and operations; therefore, a number of factors need to be considered in developing an urban meteorological network protocol (UMNP). Figure 2 and Table 2 summarize the proposed UMNP components, from whole network operations metadata to individual sensor metadata. The elements are derived from urban network literature (e.g., Mikami et al. 2003; Basara et al. 2010; Koskinen et al. 2011; Muller et al. 2013), recommendations available for urban stations (e.g., Oke 2004, 2006a), and larger-scale meteorological monitoring networks (e.g., Aguilar et al. 2003; WMO 2008, 2011), as well as the authors' experiences of setting up urban networks. The following sections provide an overview of each metadata component of the proposed UMNP (from the whole network scale to the individual sensor scale, concluding with the network operations-scale metadata), outlining and explaining the individual elements and their necessity for inclusion.

It should be noted at this stage that this protocol is designed as a guideline document to assist with collecting and documenting meaningful metadata, for use by the end user and those implementing and managing UMNs. UMNs are often designed for a specific purpose, and therefore have specific siting requirements depending on a number of aspects, including required network density, available equipment, applications, partners involved, site access, etc. (Muller et al. 2013). The metadata protocol is one of many tools needed to assist in UMN implementation. Others include, for example, instrumentation selection, communications selection, data protocols, network design, and management approach—each of which

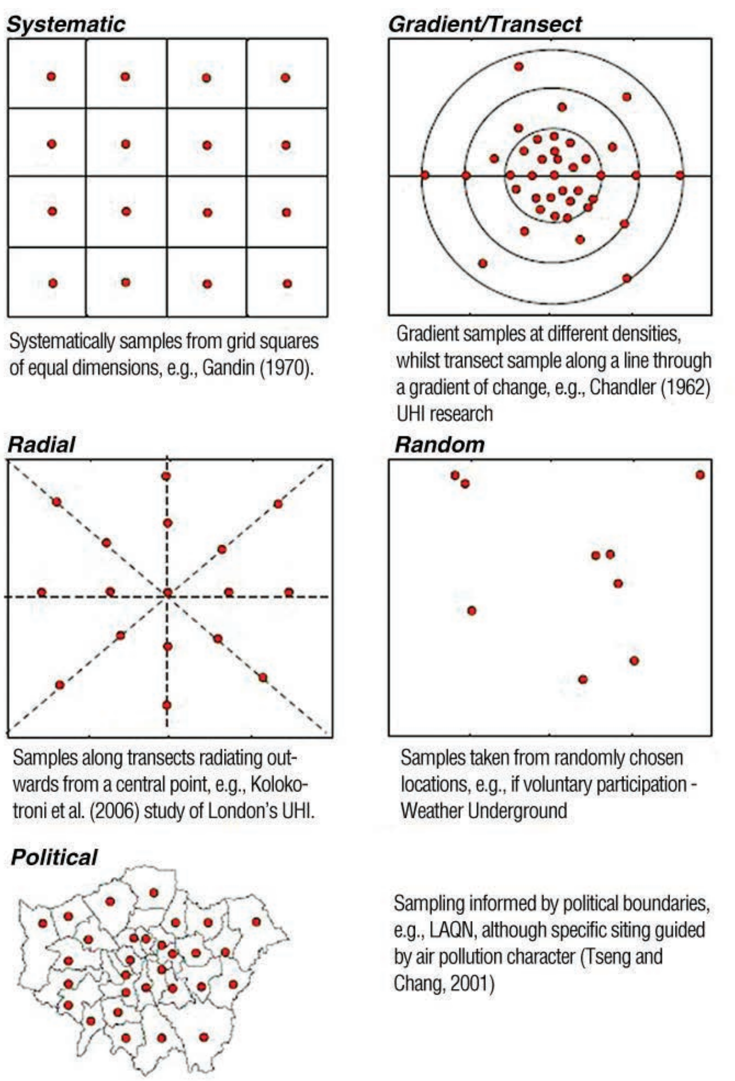

Fig. 3. Main approaches taken toward network design, with references (after Robinson 2010).

Table 2. Summary of minimum metadata required. More complete details in Tables 3, 4, 6, and 8. Letters correspond to those in Fig. 2.

(a) Network (and subnetworks)	(b) Individual station/site		(c) Instrumentation	(d) Network operations	
Network type	Site	Maintenance	Instrument	Communication network topology	Formulas
Network contact	Status	Relocation	Manufacturer	Data format	Language
Network variables	Site name	Enclosure	Model	Version numbers	Website
Network contact e-mail	Site alias (es)	Enclosure latitude	Type	Correction	Management
Network history	Type of site	Enclosure longitude	Variables	Measurement units	
Network implementation date	Latitude	Enclosure elevation	Representativeness	Missing data flag	
Network end date	Longitude	Mount location	Installation date	Language	
Network offline dates	Elevation	Type of mount	Decommissioned	Spatial resolution	
Network areal extent	Orographic setting	Height of sensor(s)	Start date	Temporal resolution	
Network spatial density	Date of metadata collection	Surface cover	End date	Time format	
Number of sites	Version number	Material below cover	Operating principals	Geographic extent	
Network map(s)	Observer	Terrain slope	Instrument communication type	Access rights	
	Start date	Building type	Data transmission frequency	Processing level	
	Stop date	Source areas	Sampling time	Other special codes	
	Instruments	Tree height	Averaging period	Metadata	
	Type of measurements	Traffic density	Precision	Server	
	Noticeable changes	Irrigation	Range	Storage	
	Station history	SVF	Response time	Backup	
	Remarks	Aspect ratio	Reporting frequency	Transmission	
	Urban structure (mean)	Moisture/heat vents	Accuracy	Access	
	Water bodies	Maps/sketches	Corrections	Archive data center	
	Mountain ranges	Photographs (winter and summer)	Known errors	Software	
	Traffic density	Relocation	Measurement units	Hardware	
	Surface cover	Site classification		Processing	
	Urban fabric			Error flags	
	Urban metabolism			QC/QA	
	Buildings (mean)			Filtering	
	Terrain			Data reduction	
	Aspect ratio			Programs	
	Maps/imagery			Algorithms	

have extensive literatures that are rapidly evolving. For example, Fig. 3 summarizes some of the main approaches toward network design; however, this also needs to take into account the land cover characteristics in the urban area when determining the appropriate number of stations and their location. Thus, how to classify urban areas—such as Stewart and Oke's (2012) local climate zones (LCZs) driven by urban heat island characteristics or Loridan and Grimmond's (2012a,b) urban zones for energy partitioning (UZE) developed for characterizing observations and for numerical modeling (Loridan et al. 2013)—needs to be part of the process of the overall UMN design. Similarly, how a UMN is managed depends on such things as the requirements of network owners, partners, number of staff employed, and resources.

Network metadata. First and foremost, details are required about the network itself (Table 3). Such network information would include the type/purpose of the network (e.g., meteorological, air pollution), a description of the network (e.g., objectives, partners), operating authority, contact details, and information regarding the operational time frame (e.g., implementation date, periods offline). Additional geomorphological, orographic, geographic, and socioeconomic data that may characterize the overall setting are also necessary (e.g., digital elevation models; census data; GIS data such as percent built, percent vegetation cover, satellite imagery, thermal imagery). Such metadata are useful for end users to appreciate the network setting and for determining land classifications, but they are also useful during the network design stages, for assisting with source area calculations (see "Site metadata" section), and for interpreting results.

Metadata management requires not only the protection of the data itself but also regular updating. Table 3 and subsequent metadata tables provide an indication of the recommended frequency to ensure that updates or changes are documented. For example, changes to the number of sites or areal extent of the network [including updated map(s)], dates when the network is offline, changes to the morphology of the area (major redevelopment, changes to specific boundaries, etc.), and vegetation characteristics (e.g., growth, planting, removal) all need to be documented.

Second, the network architecture needs documenting (e.g., number of subnetworks and individual sites, network maps, and size of the network), which will include the areal extent of the networks and the density of the array (e.g., number of sensors per area or distance between sensors). The specific size of the network will depend on its objectives, such as the atmospheric processes to be observed and the temporal and spatial resolutions required (Grimmond 2006).

Site metadata. Next, the schema includes established guidelines for individual urban meteorological stations (e.g., Oke 2004, 2006a) that are used as the basis for recommendations (Table 4). Measurements from individual sensors observe atmospheric processes from a particular source area or field of view that is representative of a specific scale. The scales of interest across and within an urban area are *mesoscale* (i.e., regional climate, covering urban, peri-urban, and rural areas), *local scale* (i.e., distinct neighborhoods), and *microscale* (i.e., urban canyons or lots) (Oke 1982, 1984, 2004, 2006b, 2009, 2006a; WMO 2008, 2011). The representativeness of individual measurements (i.e., the surrounding area an instrument "observes") or "exposure" is a function of the area influencing a measurement ("source area" or "footprint"). Source areas for many instruments and/or variables over urban areas are often difficult to calculate. They depend on the location of the instrument (e.g., height, distance to obstacles); the specific variable and temporal scale being observed; the measurement method of the instrument; the morphology of the area and the nature of the underlying surface; and in some cases, the meteorological conditions (Oke 2004; Grimmond 2006). Therefore, thorough metadata collection is paramount to inform estimates of source areas, particularly for instrumentation located within the urban canopy layer (UCL). Metadata provide additional important understanding, both about the site and the local surface characteristics that influence the measurements that are crucial to the interpretation of observations from a particular instrument.

Frequently, the siting of instrumentation in urban areas causes difficulties with respect to the representativeness of measurements. For example, it may be necessary to locate equipment over a range of surfaces (e.g., asphalt, concrete, grass) at variable heights, to split instruments over different locations, or to locate instruments nearer to buildings or anthropogenic heat/moisture sources than would otherwise be recommended by standard WMO guidelines (Oke 2004). With the impact of the urban morphology being a key aspect of the environment to be observed (Stewart and Oke 2012), the standardization of the sensor location explicitly has to relate to its 3D characteristics (height and density/spacing), rather than to the more traditional objective of being a set distance away from the roughness elements. Oke (2006b) provides

Table 3. Network level [(a) in Fig. 2] and subnetwork(s) (when the subnetworks can also standalone, the information differs) metadata directory [based on established metadata guidelines from WMO (Oke 2004, 2006a; WMO 2008, 2011), other recommendations (e.g., Aguilar et al. 2003; NRC 2009; Manfredi et al. 2005; Muller et al. 2012), individual UMN guidelines (e.g., McPherson et al. 2007; Shafer et al. 2000; Koskinen et al. 2011) plus additional elements]. Information will need to be recorded at different time intervals (R = as required, O = once).

Metadata element	Description	Time
Network administration and general information		
Network type	Type of network (e.g., climate, air pollution)	O
Network description	Purpose of network (e.g., educational/research, projects, aims, end users)	O
Project partners	Project partners (commercial, academic, local government)	R
Operating authority	Operating authority or responsible organization (e.g., university, local government)	O
Network contact	Key network contact person/manager	R
Network contact address	Address for network contact person	R
Network contact phone umber	Phone number for network contact person	R
Network contact e-mail	E-mail for network contact person	R
Network variables	Variables monitored (temperature, wind, rainfall, pressure, etc.)	R
Network history	General historical network information (e.g. social, political, institutional changes or any other significant changes)	R
Operational time frame		
Network implementation date	Network implementation date	O
Network end date	End date (if applicable)	O
Network offline dates	Periods when offline	R
Size of network		
Network areal extent[a]	Areal extent of network[a] (regional/mesoscale; city, local scale/neighborhood; microscale, specific area)	R
Network spatial density[a]	Spatial density[a] (coarse array, wide array, fine or dense array, microarray)—based on distance between sensors (i.e., km^{-2})	R
Number of subnetworks	Number of subnetworks (e.g., nested network across the same area)	R
Number of sites	Number of sites within network (including reference stations)	R
Network map(s)	Maps of network layout and sites	R
Network geomorphology	Geomorophological data for the network area	R
Network orography	Orographic setting of the area (e.g., Wanner and Fillinger 1989)	R
Geographic/socioecomic data	Geographic and socioeconomic information about the network area (i.e., population, land use, wards, etc.)—wide ranging	R

[a] See Table 7 for proposed definitions of classifications.

TABLE 4. Site and enclosure(s)-level [(b) in Fig. 2] metadata directory [based on established metadata guidelines from WMO (Oke 2004, 2006a; WMO 2008, 2011), other recommendations (e.g., Aguilar et al. 2003; NRC 2009; Manfredi et al. 2005; Muller et al. 2013), individual UMN guidelines (e.g., McPherson et al. 2007; Shafer et al. 2000; Koskinen et al. 2011) plus additional elements]. Information will need to be recorded at different time intervals (H = hourly, D = daily, W = weekly, S = seasonal, A = annual, R = as required, O = once).

Metadata element	Description	Time
	Station administrative and geographical information	
Site identification	Station identifier or code	O
Status	Active/closed	R
Site name	Station name (i.e., town or village, school name)	O
Site alias(s)	Any alternative name(s) the station may be known by	R
Type of site	Station type (i.e., meteorological, hydrological, air pollution, etc.)	O
Latitude	Latitude (in units of 0.0001°N/S)	R
Longitude	Longitude (in units of 0.0001°E/W)	R
Datum	Precise datum used	O
Elevation	Elevation (MSL)	R
Orographic setting	Orographic setting of the site (e.g., Wanner and Fillinger 1989)	A
Location	Relative location of site within area (e.g., urban fringe, urban core, rural)	A
Site address	Address of station location	R
Site contact person[a]	Contact person/person responsible	R
Site phone number[a]	Phone number for site contact/person responsible	R
Site contact e-mail[a]	E-mail for site contact/person responsible	R
Date of metadata collection	Date of metadata collection/update/revision	R
Version number	Version number of metadata (e.g., if alterations made, such as instrument moving, site changing)	R
Frequency of visits	Frequency of visits to update metadata, check sites, equipment, etc.	A
Observer	Person(s) collecting the metadata	R
Start date	Date station started recording observations (opening date)	R
Stop date	Date station stopped recording observations (closing date)	R
Power supply	Power supply type (if necessary), e.g., mains, solar, battery	R
Instruments	List of instruments on site (e.g., rain gauge, temperature sensor)—includes details such as type/make of instrument	R
Type of measurements	Meteorological variables measured (i.e., temperature, wind, precipitation—direct and indirect measurements)	R
Noticeable changes	Noticeable changes since last visit (occurring at each visit)	R
Station history	Station history—changes the site has undergone during its lifetime (linked to maintenance log and QA/QC), i.e., changes in sheltering and exposure, land use changes, changes to instrumentation, etc.	R
Remarks	Notable remarks about station/points to highlight	R

Continued on next page.

Table 4. Continued.

Metadata element	Description	Time
	Site communications/data transmission [also part of network operations, (d) in Fig. 2]	
Communications type	Wired/wireless facilities [including type, i.e., ZigBee, Wi-Fi, local area network (LAN), broadband, dial-up]	R
Signal transport information[a]	Any additional information related to signal transport (i.e., type, type and modification of signal modification unit, length and type of cables, etc.)	R
Communications name[a]	Network name [e.g., name of the Wi-Fi network, service set identification (SSID)]	R
Communications password[a]	Network password/passkey	R
Communications backup[a]	Is there a backup solution for times when the network is unavailable? What?	R
Technical information[a]	Additional information required for data transmission [e.g., Internet protocol (IP) address, subnet mask, gateway, encryptions, etc.]	R
Communications network owner[a]	Communications network owner (e.g., school, authority)	R
ICT contact[a]	Contact details for the relevant information communications technician	R
	Local-scale survey[b]	
	Urban structure (typical): Fetch—similar or patchy—values by direction (min, mean, max)	
Building spaces	• Spaces between buildings (m)	A
Building density	• Building density (buildings per square meter)	A
Street widths	• Street widths (m)	A
Tree height	• Tree height (m)	S
Tree species	• Tree species (e.g., deciduous, coniferous—possibly specific type)	S
Water bodies	Proximity and size of water bodies	A
Mountain ranges	Mountainous areas across the locale	A
Traffic density	Traffic density (e.g., none, light, medium, heavy)	D, W, H
Surface cover	Surface cover (percent built, percent vegetated, percent bare soil, percent impervious, percent water)	A
Urban fabric	Urban fabric (construction, impermeable and natural materials)	A
Urban metabolism	Urban metabolism (heat, water, pollutants)	A
	Buildings (typical)	
Stories	• Number of stories	A
Roof types	• Roof type (e.g., flat, slanted)	A
Roof material	• Roofing material (e.g., clay tile, asphalt)	A
Building materials	• Materials (e.g., brick, concrete, wood)	A
Building types	• Residential detached/attached/school, etc.	A
Building age	• Age	A
Terrain	Slope (steepness and direction)	A

Aspect ratio	Aspect ratio [height of main roughness element divided by average spacing (Z_H/W)]	A
	Maps/imagery	
Local maps	• Local to mesoscale maps (~1:5000; ~1:25,000; and ~1:100,000)	A
Aerial photography	• Aerial photographs	S
Sketch map	• Annotated sketch map of local environment	S
Satellite imagery	• Satellite imagery (optical, infrared)	S
Relocation	Dates of station relocation	R
Microscale survey for each separate instrument enclosure on site[b] (information essential for assessing instrument exposure)		
Enclosure	Name to identify the enclosure (if more than one at a site)	R
Enclosure latitude	Latitude (in units of 0.0001°N/S)—for separate enclosure (if necessary)	R
Enclosure longitude	Longitude (in units of 0.0001°E/W)—for separate enclosure (if necessary)	R
Enclosure elevation	Elevation (MSL)—for separate enclosure (if necessary)	R
Mount location	Mount location and shelter description (i.e., lamppost, sign, fence, etc.)	R
Type of mount	Type of mount (i.e., on mast, post, tripod, open lattice guyed, etc.) and description; height above surface	R
Height of sensor(s)	Height of sensor(s) above ground level [for each instrument, (c) in Fig. 2, e.g., thermometer, gauge rim, anemometer heights]	R
Surface cover	Surface cover below station (i.e., artificial surfaces, agricultural surfaces, natural vegetation and open areas, wetland, and water bodies and types)	S
Material below cover	Soil/material below cover (type, profile)	S
Terrain slope	Slope of terrain (steepness and direction)	A
Building type	Building types (number of stories, roof type, materials, detached/attached, age, etc.)	A
Source areas	Source areas (footprints) for radiation and turbulence	S
Tree height	Mean tree height Z_T and locations	S
Traffic density	Traffic density (i.e., none, light, medium, heavy)	W,D,H
Irrigation	Proximity to irrigation and frequency (where applicable)	S
SVF	Optical, or use horizon method below	S
Horizontal distances	Horizontal distance to buildings W (m)	A
Building heights	Height of buildings Z_H (m/story)	A
Aspect ratio	Aspect ratio	S
Moisture/heat vents	Presence of moisture or heat vents	S
	Maps/sketches	
Horizon map	• Radiation horizon map (aids SVF and building height estimates)	S
Sketch map	• Sketch map of microscale environment surrounding instrument location	A
Enclosure diagram	• Sketch map/diagram of instrument enclosure/mount layout	A

Continued on next page.

Table 4. Continued.

Metadata element	Description	Time
	Photographs (winter AND summer)	
Site photo	• Photograph of the station locations	S
Cardinal photos	• Photos from cardinal directions of instrument	S
Panoramic photos	• Panoramic photo	S
Fisheye photo	• Fisheye photo (to calculate SVF)	S
Relocation	Dates of instrument relocation	R
Maintenance	Routing maintenance log [i.e., station inspection, equipment inspection, instrument checks, recalibrations, replacements, malfunctions, corrections, cleaning, mowing, instrument relocations (Note: if instrument is moved, then a new station number or updated metadata with version number is required)]—part of QA/QC procedures in (d) in Fig. 2	R
Site classification, based on classification criteria methods[c], e.g.,		
LCZ[c]	Local climate zones (Stewart and Oke 2009, 2012)	A
UCZ[c]	Urban climate zones (Oke 2004)	A
UTZ[c]	Urban terrain zones (Ellefsen 1991)	A
DRC[c]	Davenport roughness class for terrain roughness (Davenport et al. 2000)	A

[a] Information kept private for network managers/technicians only—not supplied as metadata to end user.

[b] Please see supplemental material, e.g., UMN station metadata documentation template.

[c] See Table 5 for overview of classification schemes.

a detailed recommendation for locating instruments, primarily for those within the UCL, and for calculating source areas. There continues to be a need for more developments in source area modeling for use within the UCL and above that are applicable beyond neutral conditions.

Given the dynamic nature of urban areas, the site metadata should also include maps, photographs, aerial photography, sketches, geographic information, site descriptions, and maintenance logs at regular intervals. Site or station metadata require local scale and microscale site surveys. Currently, approximate and arbitrary areas of 500 m × 500 m and 50 m × 50 m, centered on the sensor site, are designated for conducting the local-scale and microscale surveys, respectively, since it has been found that on average the source area for a screen-height temperature sensor in neutrally stable atmosphere is no more than a few hundred meters (Tanner 1963; Mizuno et al. 1990/1991; Runnalls and Oke 2006; Stewart and Oke 2012). However, since the precise domain (size, shape, orientation) of these source areas does vary with meteorological conditions, stability, and the temporal resolution being investigated, conducting source-area analyses using a footprint model (e.g., Kljun et al. 2002; Schmid 2002) would be ideal and may be required for certain UMN applications. Stewart and Oke (2012) discuss this in more detail and provide a good illustration in Fig. 5 of their paper.

Site surveys will examine the structure of the area (building types, materials and mean heights, roof types, mean tree heights, distance between buildings, etc.), urban cover (e.g., built up, vegetated, water, soil), urban fabric (e.g., road, wall materials), and urban metabolism (e.g., anthropogenic activities, anomalous and typical heat, water and pollutants, traffic density) at the respective scales (Oke 2006a). Tracking disturbances in the area (e.g., from roadwork and construction) is important but may be difficult at many sites. With the increasing availability of lidar datasets, digital surface models (DSMs), and aerial imagery, the local and microscale 3D morphological influences can now be readily identified (e.g., Kidd and Chapman 2012). Additional site surveys provide key additional information about vegetation, materials, and nearby activities (e.g., vehicle parking, vent locations) relative to the instruments. The microenvironmental factors (building types, materials, heights, distance between buildings, roof types, tree heights, surface material, traffic density, heat/moisture vents, etc.) include creating sketch maps (radiation horizon, site sketch map), taking numerous photographs of the site (e.g., location, cardinal directions, panoramic, and hemispherical), documenting location information (e.g., latitude, longitude, elevation), and other factors [sky view factor (SVF), aspect ratio, heights of sensors, etc.]. Since instruments can be placed at different locations within a site (e.g., on masts and rooftops, at more open locations, in different enclosures), different microscale surveys are required for each instrument enclosure.

Standardized site information is needed so data users are aware of site variations, since they rarely have the luxury of being able to visit each station across a network (Oke 2006b). If adequate metadata are available, then this should not create limitations for end users. Indeed, the majority of urban heat island studies fail to communicate the physical nature of the surfaces surrounding the instruments (Stewart 2011). To characterize urban locations for meteorological and climatological purposes, a number of schemes have been proposed (e.g., Table 5). However, no standard presently exists (Basara et al. 2010) and the current schemes may not be internationally applicable or definitive, as sites may fall into more than one category. It is therefore important that generalized and/or customized classification techniques implemented for interpreting results be documented and the assigned type reported for all sites. Critical details that should be documented include the area used for classification (e.g., 100 m^2, 500 m^2, 2 km^2), the source of data (e.g., year, aerial photos, ground surveys), and the assumptions (e.g., dominant, weighted average) for repeatability and consistency. The complete station history (maintenance logs, metadata updates) is also essential, so instrumental and site changes can be distinguished, and will include dates and details of any changes; interruptions; inspection visits; and comments about the exposure, quality of observations, changes to the site, and operations (WMO 2011).

While many aspects of this UMNP are designed to aid with the collection of high-quality data and to assist the end user with data analysis (QA/QC, station metadata, representativeness, etc.), there are other aspects specifically to assist network owners, managers, and technicians, since it is also important to provide guidance for the implementation and running of an UMN to ensure that networks are efficiently established. Therefore, additional elements are required for sites that form part of an UMN—for example, information about the local communications network or local node that is being used to transmit the data [this will vary for each UMN and depend on the type of information required; however; e.g., it may include network type, encryptions, passwords, etc., which are also part of the "network operations" component (see "Network operations metadata" section)] and the relevant contact details [e.g., if a school site is used, then it might be useful to have liaison details for information and communications technology (ICT) staff]. Furthermore, since access to different elements of the metadata will vary, it is expected that some of the metadata are stored in an encrypted format and not released to most end users (e.g., passwords, network information, personal details, and other details to comply with data protection laws). Thus, only the portion of the metadata regarded as useful to the end user would be initially provided with the data. This would be managed by the UMN data manager or technician.

Aguilar et al. (2003) and Oke (2004, 2006a) provide templates for collecting the minimum information necessary for individual urban stations. Based on these, an adaptable UMNP station metadata template (see supplementary material at http://dx.doi.org/10.1175/BAMS-D-12-00096.2, along with a completed example) has been developed with additional elements included (e.g., information on the communication network, contacts, instrumentation, type of site). Collection of these metadata in the field should typically take no more than 30 min, with some additional time required (prior to and postfield collection) using Internet-based resources (such as Google Earth, GIS, satellite datasets, etc.) to explore the local area (to determine land classifications, Davenport roughness class, land cover, etc.) and to collate additional logistical and instrumental data. The aim of this template is to facilitate the regular update of station metadata in order to assess any changes occurring at the sites, which can then be used in conjunction with the detailed account of the station history (whether equipment has been moved, replaced, etc.). It is expected that individual UMNs will need to adapt the form for their specific needs—for example, not all fields may be required and/or additional fields may be necessary. However,

Table 5. Examples of urban site classification schemes.

Terrain roughness length—based on Davenport et al. (2000) classification for urban roughness

No.	Class name	Roughness length z_0 (m)	Landscape description
1	Sea	0.0002	Open water, featureless plain, fetch > 3 km
2	Smooth	0.005	Obstacle-free land with negligible vegetation; marsh, ridge-free ice
3	Open	0.03	Flat open grass, tundra, airport runway; isolated obstacles separated by >50 obstacle heights H
4	Roughly open	0.10	Moderately open country with occasional obstacles (i.e., isolated low buildings or trees) at relative horizontal separations of >20H
5	Rough	0.25	Scattered obstacles (buildings) at relative distances of 8–12H for low solid objects
6	Very rough	0.5	Area moderately covered by low buildings at relative separations of 3–7H and no high trees
7	Skimming	1.0	Densely built-up area without much building height variation
8	Chaotic	≥2	City centers with mix of low- and high-rise buildings

UTZ from Ellefsen (1991)

Attached UTZ		Detached building (close set) UTZ		Detached building (open set) UTZ	
A1	Attached buildings; commercial offices, retail; core area; low rise; mass and framed constructions; constructed from earliest times through to present	Dc1	Detached buildings; commercial office; high-rise; light-clad framed; built since 1950	Do1	Detached buildings; shopping centers; beyond core; low rise; mass and framed construction; post WWII
A2	Attached buildings; apartments/hotels; near core area; complete fitting of block frontages; four or more stories high; built mostly in the pre-World War II (WWII) period	Dc2	Detached buildings; residential apartments/row houses; >75% block frontages; widely distributed locations; built through to present	Do2	Detached buildings; residential apartments and low housing; less than 75% block frontages; low to medium rise; widely distributed locations; low rise to high-rise; built largely since the end of WWII
A3	Attached buildings; apartments and abutted-wall houses; adjacent to core area; fewer than four stories; mostly pre-WWII	Dc3	Detached buildings; residential houses; 75% and more block frontage; widely distributed locations; built through the present	Do3	Detached buildings; houses; less than 75% frontage; low rise; widely distributed locations; built through to present
A4	Attached buildings; industrial/storage; near core area; on ordered blocks with little or no setback; medium rise; mass and framed construction; built mostly pre-WWII	Dc4	Detached building; industrial/storage; linear building pattern; railroad or dock related; low rise; built through the present	Do4	Detached buildings; industrial/storage; truck related; widely distributed locations; ordered pattern (buildings fairly evenly spaced; separated by parking lots, storage areas); low rise; post 1920s
A5	Attached buildings; commercial ribbon development; on some arterials outward from core area and elsewhere; virtually complete filling of block frontages along street; low to medium rise; built mostly pre-WWII	Dc5	Detached buildings; elder commercial ribbons; along pre-WWII string streets; limited off street; parking; low rise (fewer than five stories)	Do5	Detached buildings; modern commercial; ribbon development; along major new arterials; open pattern (buildings separated by intervening parking lots and open storage areas); low rise (fewer than five stories); post early 1950s
		Dc8	Detached buildings; commercial (outer city); at metropolitan-area periphery; high-rise; light-clad framed; built early 1950s through to present	Do6	Detached buildings; administrative/cultural (i.e., government, schools, hospitals); low to medium rise; widely distributed locations; ordered building pattern; built through to present

Simplified set of classes based on the above-mentioned classification schemes—see Oke (2004) for images associated with each UCZ

UCZ	Approximate UTZ	Descriptions	DRC	Aspect Ratio [Z_H/W – average height of the main roughness elements (buildings, trees) divided by their average spacing]	Percentage built [average proportion of the area covered by impermeable surfaces (i.e., buildings, pavements, roads, etc.)]
1	Dc1, Dc8	Intensely developed urban with detached close-set high-rise buildings with cladding, i.e., central business district skyscrapers	8	>2	>90
2	A1–A4, Dc2	Intensely developed high-density urban with 2–5 stories; attached or very close-set buildings, often of brick or stone, i.e., old city core	7	1.0–2.5	>85
3	A5, Dc3–5, Do2	Highly developed medium-density urban with row houses or detached but close-set houses; stores and apartments, i.e., urban housing	7	0.5–1.5	70–85
4	Do1, Do4, Do5	Highly developed, low- or medium-density urban, with large low buildings; paved parking, i.e., shopping centers, warehouses	5	0.05–0.2	70–95
5	Do3	Medium-developed low-density suburban, with 1- or 2-story houses, i.e., suburban housing	6	0.2–0.6 (up to >1 with trees)	35–65
6	Do6	Mixed use with large buildings in open landscape i.e., hospitals, universities, airports	5	0.1–0.5 (depends on trees)	<40
7	None	Semirural development; scattered houses in natural or agricultural areas, i.e., farms, estates	4	>0.05 (depends on trees)	<10

LCZs—see Stewart and Oke (2012) for methods, sketches, photographs, full descriptions, and associated values and properties

Code	Zone	Definition	SVF	Aspect ratio	DRC	Impervious surface fraction
LCZ-1	Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials	0.2–0.4	>2	8	40–60
LCZ-2	Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	0.3–0.6	0.75–2	6–7	30–50
LCZ-3	Compact low rise	Dense mix of lowrise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	0.2–0.6	0.75–1.5	6	20–50
LCZ-4	Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	0.5–0.7	0.75–1.25	7–8	30–40
LCZ-5	Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	0.5–0.8	0.3–0.75	5–6	30–50

Continued on next page.

Table 5. Continued.

LCZs—see Stewart and Oke (2012) for methods, sketches, photographs, full descriptions, and associated values and properties						
Code	**Zone**	**Definition**	**SVF**	**Aspect ratio**	**DRC**	**Impervious surface fraction**
LCZ-6	Open low rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, concrete construction materials.	0.6–0.9	0.3–0.75	5–6	20–50
LCZ-7	Lightweight low rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	0.2–0.5	1–2	4–5	<20
LCZ-8	Large low rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	>0.7	0.1–0.3	5	40–50
LCZ-9	Sparsley built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	>0.8	0.1–0.25	5–6	<20
LCZ-10	Heavy industrial	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard packed. Metal, steel, and concrete construction materials.	0.6–0.9	0.2–0.5	5–6	20–40
LCZ-A	Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.	<0.4	>1	8	<10
LCZ-B	Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.	0.5–0.8	0.25–0.75	5–6	<10
LCZ-C	Bush, scrub	Open arrangement of bushes; shrubs; and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.	>0.9	0.25–1.0	4–5	<10
LCZ-D	Low plants	Featureless landscape of grass or herbaceous plant cover. Few or no trees. Zone function is natural grassland, agriculture, or urban park.	>0.9	<0.1	3–4	<10
LCZ-E	Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.	>0.9	<0.1	1–2	>90
LCZ-F	Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture	>0.9	<0.1	1–2	<10
LCZ-G	Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.	>0.9	<0.1	1	<10

we highlight those elements considered "mandatory" (e.g., latitude, longitude, elevation, local-scale sketch map and information, microscale sketch map and information, and station and cardinal photographs). Once the metadata have been collected during the initial installation, they can be input electronically (into a form and/or a database), used for subsequent visits, and quickly updated. Indeed, with the recent proliferation of smart devices/tablets, updating can now be done quickly and directly in the field. Overall, this would form part of the network QA/QC procedures (see the "Network operations metadata" section) and is an essential part of the station metadata to ensure homogeneity (Aguilar et al. 2003).

Instrumentation metadata. As with existing site protocols, separate information is mandatory for each piece of equipment at each site (Table 6), including information about the instrument itself (e.g., manufacturer, model, serial number, installation and calibration dates, and calibration and testing results; see also the "Network operations metadata" section). Operational instrument-specific information about the communication system will need to be safely documented (passwords, IP address, MAC address, etc.—see Table 6 for detailed list).

Some instruments incorporate multiple sensors (e.g., temperature and humidity) or multiple variables are obtained (e.g., wind components, virtual temperature), so additional metadata are required for each sensor and/or variable. This includes information specific to the sensor (height of gauge rim above ground for precipitation, type and size of screen for temperature, etc.) in addition to performance characteristics of the sensor (sensitivity, range, etc.) and data and/or measurement characteristics (sampling time, averaging periods, etc.).

The *representativeness* of each measurement or "instrument exposure" (see "Site metadata" section) will also need documentation. As highlighted in Muller et al. (2013), the use of "scale"-related terms can cause confusion when applied to networks, as information on network and station scales is often difficult to establish since it is not explicitly stated, is unclear, or uses inconsistent terminology to define urban sensor networks. Specifically, this relates to the distinction between spatial or areal *extent* of the network, which is often reported as the "network scale" or "network size" (see "Network metadata" section), spatial *resolution* or *density* of the network (which is dependent upon the density of individual sensor sites), and spatial representativeness or *scale length* of the individual measurements (which is dependent on the actual location of the instrumentation, measurement interval, and exposure; Oke 2006a). This "confusion of scales" has recently been highlighted as a common flaw in urban climate investigations (Stewart 2011) and is particularly true of urban networks. For example, a sensor network may be classified as a "mesoscale network" since it covers hundreds of square kilometers consisting of urban, suburban, and rural areas. However, the representativeness of the individual sensors or monitoring stations, and the number of sensors in the network could be classified on very different scale. Hence, a network areal extent may be "mesoscale" but the individual measurements could be more representative of mesoscale, local scale, or microscale processes. Presently, and in most cases, UMNs have been defined solely by their spatial extent. Although information about the number of sensors and location of sensors is often given, information about "network density" and "representativeness" of measurements should be explicitly defined, since it affects both the application of the network and what is appropriate with cross network comparisons (Oke 2004, 2006a).

The proposed network-scales UMN classification scheme is given in Table 7. The areal extent or size, the spatial density, and the representativeness of individual monitoring stations within the network are the key descriptors.

Network operations metadata. Details of network operation (Table 8) can be broken down into hardware components and cyberinfrastructure, which includes the data flow from the sensor to initial analysis, data management, data display, and usage (Hart and Martinez 2006; Muller et al. 2013). This consists of computer systems, instrumentation, data acquisition, data storage systems and repositories, visualization systems, management services, and technicians, linked by software and communications networks (Estrin et al. 2003; Brunt et al. 2007; Muller et al. 2013).

Hardware and cyberinfrastructure. Documentation of the hardware assets of a network (e.g., sensors, loggers, communications, and computers) is important not only for reporting purposes but also for keeping track of equipment, especially important for wide-area deployments. Recorded information should be as extensive as possible, with make, model, manufacturer, serial number, purchase date, and current location being minimum requirements for hardware in storage. However, for equipment deployed in the field (i.e., sensors), much more detailed information is required.

Table 6. Instrumentation-level [(c) in Fig. 2] metadata directory [based on established metadata guidelines from WMO (Oke 2004, 2006a; WMO 2008, 2011), other recommendations (e.g., Aguilar et al. 2003; NRC 2009; Manfredi et al. 2005; Muller et al. 2013), individual UMN guidelines (e.g., McPherson et al. 2007; Shafer et al. 2000; Koskinen et al. 2011) plus additional elements]. Information will need to be recorded at different time intervals (Se = seconds, M = minute, H = hour, D = daily, W = weekly, S = seasonal, A = annual, R = as required, O = once)

Metadata element	Description	Time
Instrument administrative information		
Instrument ID	Instrument number (specific to the network/project)	O
Manufacturer	Manufacturer and part numbers	O
Make	Make of instrument/sensor	O
Model	Model	O
Size	Approximate size of instrument	O
Type	Type of instrument(s) (e.g., thermister, radar wind profiler, cup anemometer)	O
Variables	Variables monitored (e.g., air temperatures, relative humidity, rain rate, etc.)	O
Serial number[a]	Serial number for sensor	O
Installation date	Date of installation/upgrade	O
Decommissioned	Date taken offline/decommissioned (if applicable)	R
Start date	Start of data collection	O
End date	End of data collection	O
Operating principals	Operating principals (specific to network)	R
Condition	Condition (age)	R
Power supply	Power supply (battery, solar, mains)	R
Transducer	Transducer type (if applicable)	O
Local data storage	Local data storage capabilities (i.e., datalogger)	R
Representativeness[b]	Representativeness of measurement[c] (e.g., mesoscale, local scale, microscale)	R
Details specific to sensor type[c]		
Temperature and relative humidity	Type and size of screen and ventilation (temperature and humidity)	O
Wind	Method of azimuth alignment (wind)	O
Precipitation	Type and gauge rim diameter, rim height above ground, presence of heating device (precipitation)	O
Sunshine	Type and thresholds for automatic sunshine recorders (sunshine)	O
Evaporation	Any coverage applied to evaporation pan (evaporation)	O

Instrument communications/data transmission [also part of network operations (d) in Fig. 2]		
Instrument communications type	Wired/wireless (including type, i.e., ZigBee, Wi-Fi, LAN, broadband, dial-up)	R
Media access control (MAC) address[a]	Instrument MAC address	O
Password[a]	Password if needed	R
One-way/two-way communications[a]	One-way/two-way communications?	R
Data transmission frequency	Frequency of data transmission	R, D, H, M
Sampling time	Time of observations (and No. of observations)	R, D, H, M, Se
Averaging period	Output averaging period	R, D, H, M, Se
Precision	Sensitivity/precision	O
Range	Measurement range	O
Response time	Response time	R, D, H, M, Se
Reporting frequency	Reporting frequency	R, D, H, M, Se
Accuracy	Accuracy (uncertainty)	O
Corrections	Corrections/calibration constants	A
Known errors	Known errors	A
Measurement units	Measurement units	O

[a] Information kept private for network managers/technicians only—not supplied as metadata to end user.

[b] See Table 7 for proposed definitions of classifications.

[c] There will be a specific set of features that need reporting depending upon the specific type of instrument—please refer to WMO guidance for details.

This includes a description of what the sensor observes [variable(s)], observation method (e.g., direct observation or sampling), observation frequency/period, performance characteristics (e.g., resolution, precision, range, and accuracy), calibration information (e.g., date since last calibration, method, and calibration coefficients), and deployment dates (see Table 8 for a complete list). Records should be kept throughout the sensor deployment of any site visits, problems encountered, changes around the location, and routine/nonroutine maintenance. These records not only provide a history that can be referred to to highlighting issues encountered, but also form an important part of network QA/QC procedures (Fiebrich et al. 2010).

Dense sensor networks may be installed to explore spatiotemporal variability across heterogeneous urban terrain. However, the reliability of the observed variability across a network may be significantly compromised by observation errors, and instrument drift and failure. To minimize these impacts and to ensure any observed fluctuations are credible, a proactive approach to instrument calibration is recommended as part of QA/QC procedures. This approach requires predeployment (both in the laboratory and field), routine site visits (including onsite testing) and postdeployment calibration of each sensor across the network with the methods utilized and frequency clearly stated within the metadata (Shafer et al. 2000; McPherson et al. 2007; Fiebrich et al. 2010).

Table 7. Overall UMN scale classification requires all three components to be specified.			
Areal extent/size of network			
Climate scale	**Orlanski (1975)**	**Network covers**	**Spatial area (function of urbanized and nonurbanized extent) (km^2)**
Mesoscale/regional	Meso-α	Urban, suburban and rural areas	10^2–10^4
City	Meso-β	Whole city	10–10^3
Local/neighborhood	Meso-γ	A neighborhood with similar urban development	10^{-1}–10
Microscale	Micro-γ, -β, -α	Small areas of neighborhoods (e.g., street canyons)	10^{-6}–10^{-1}
Spatial density of network			
Array classification	**To assess**	**Mean distance between sensors**	
Coarse array	Large-scale variations	>10 km	
Wide array	Medium-scale variations	1 km–10 km	
Fine or dense array	Small-scale variations	100 m–1 km	
Micro array	Microscale variations	<100 m	
Representativeness of individual measurements		**Location criteria/siting requirements**	
Scale length	**Sensor measurements representative of**	**Sensors sited to take measurements**	
Mesoscale	Climate across the region	Representative of the wider mesoscale region; a single canopy-layer station cannot adequately represent climate across an urbanized area (Oke 2004)—scale relevant for boundary layer instrumentation	
Local scale	Climate over the local area	Avoid microclimate effects and collect measurements that are representative of the local area	
Microscale	Microscale climate variations	Examine microclimates, e.g., side of building, on roof of building, street canyon	

A simple review of the manufacturer calibration certificate should aid assessment of what was used as the reference instrument and its associated quality. Calibration against international standards is preferred but a traceable reference/working standard is acceptable (WMO 2008). Similarly, in-house calibrations need to consider the quality of the reference instrument. In-house interinstrument comparisons are critical prior to and after network deployment. The results of performance tests, QA/QC procedures, calibration, intercomparisons, research, processing, management techniques, and technical specifications should be made available and easily obtainable through peer-reviewed literature, conference papers, presentation, technical notes, and end-user guides using standardized terms (e.g., metadata, scales) (McGuirk and May 2003; Oke 2006b; Stewart 2011).

Cyberinfrastructure elements include network communications (e.g., wireless sensor node topology, mode of transmission, frequency of transmission), equipment and data processing techniques (which are critical prior to and after data collection), dataset information (e.g., data formats, measurement units, time formats, processing levels, calibration coefficients, constants), data management (e.g., QA/QC, error reporting, missing data flags, filtering, algorithms, programming language/software), and data storage (e.g., servers and storage media used, data backup, where archived, how to access).

Reporting, and communication and information dissemination. Entire network-level metadata will require regular updates and need to be easily obtainable in electronic form via appropriate inventories and catalogues (WMO 2011). The entire network metadata will be encoded, stored, and distributed: with the data itself as an accompanying text file [e.g., comma-separated values (CSV) file] or database {e.g., online using My Sequel (MySQL), Oracle, PostgreSQL, or as attribute data contained within the data file itself [e.g., network Common Data Form (netCDF), hierarchical data format (HDF), gridded

Table 8. Network-operations-level [(d) in Fig. 2] metadata directory [based on established metadata guidelines from WMO (Oke 2004, 2006a; WMO 2008, 2011), other recommendations (e.g., Aguilar et al. 2003; NRC 2009; Manfredi et al. 2005; Muller et al. 2013), individual UMN guidelines (e.g., McPherson et al. 2007; Shafer et al. 2000; Koskinen et al. 2011) plus additional elements]. Information will need to be recorded at different time intervals (refer to Fig. 6). BADC = British Atmospheric Data Centre. NASA = National Aeronautics and Space Administration. NERC = Natural Environment Research Council.

Metadata element	Description	Time
Hardware testing [also part of instrumentation, (c) in Fig. 2]		
Instrument testing	Details on testing of instrument (laboratory/field, intercomparisons, equipment involved)	O
Sensor calibration	Calibration procedures (methods, details, results)	O, A
Traveling calibration	Results of comparisons with traveling standards (for each instrument)	A
Network cyberinfrastructure [see (c) instrumentation for communications details specific to instrument and site in Fig. 2]		
Communications network topology	Arrangement of wireless devices (if applicable)	R
Transmission	Mode of transmission (e.g., landline, wireless, uplink to satellite)	R
Observing practices for reported datasets and metadata[a]		
Data format	Data format(s)	R
Version numbers	Details on version numbers linked with station history and instrument maintenance logs (i.e., if equipment moved, version number updated)	R
Correction	Postcollection correction or offset to be applied	R
Measurement units	Measurement/scale units	R
Missing data flag	Details on when missing data are flagged	R
Language	Programming language used	R
Spatial resolution	Spatial resolution	R
Temporal resolution	Temporal resolution	R
Time format	Standard time (UTC)	R
Geographic extent	Geographic/areal extent of the network	R
Access rights	Access rights for different users/different metadata	R
Processing level	Processing level (raw, processed)	R
Constant(s)	Constant(s) and parameter values	R
Other special codes	Other codes reporting special circumstances, i.e., missing data, errors, wrong values, suspicious data, trace precipitation, etc.	R
Metadata	Digitized metadata system (e.g., KML, GML, netCDF, database, etc.)—including all metadata information	R
Data storage		
Server	Servers used (in house, external)	R
Storage	Storage media type	A, D, H

Continued on next page.

Table 8. Continued

Metadata element	Description	Time
Back-up	Backup storage information	A, D
Transmission	How data are transmitted (to server, end user)	R, D, H, M
Access	Details on how and where to access data	R
Archive data center	Archive at data center (e.g., BADC, NASA, NERC)	A, D
Software	Software used/recommended	R
Hardware	Hardware and operating platform(s) (e.g., Windows, UNIX, Linux, Mac)	R
Data management methods		
Processing	Processing techniques (on-site/off-site)	R, D, H, M, Se
Error flags	Error reporting/flags [if adjustments are made, or missing data are filled, then this would include information regarding percentage missing data, algorithms employed (i.e., for interpolation schemes); period for which data were interpolated etc.]	R, D, H, M, Se
QC/QA	Data QC/QA methods (i.e., gross error check, tolerance tests, internal consistency checks, temporal coherency, spatial coherency, homogeneity adjustments plus additional information regarding amended data or procedures (i.e., percentage missing data, algorithms used, data period, etc.)	R, A, D, H, M, Se
Filtering	Filtering techniques used	R, A D, H, M, Se
Data reduction	Data reduction methods	R, A, D, H, M, Se
Programs	Programs used	R, A, D, H, M, Se
Algorithms	Details of specific algorithms	R, A, D, H, M, Se
Formulas	Formulas for calculations	R, A, D, H, M, Se
Language	Programming language used	R
Other		
Power[b]	Power source, power backup options, power management	R
Website	Website [uniform resource locator (URL), real-time visualization, data display, information)]	R, A, D, H, M
Staff	Staff (technicians, researchers, managers)	R
Management	Network management, monitoring, and maintenance procedures	O, R, A, D

[a] This does not include the complete list of information required for electronically reporting "dataset metadata"—this would be based on the information collected following this protocol, but it would also include additional elements specific to the dataset itself and chosen method of reporting (i.e., identifiers, character set, dataset period, version numbers, file formats, geographic bounding information, etc.). There are also specific terminologies, definitions, codes, and a standard format for reporting metadata—please refer to the main text for more information on standards for encoding and reporting metadata electronically.

[b] Information kept private for network managers/technicians only—not supplied as metadata to end user.

binary (GRIB), and binary universal form for the representation of meteorological data (BUFR) to list but a few but many other acceptable formats]}. Encoding methods such as extensible markup language (XML) provide a logical choice of format for this purpose and are already recommended by WMO as the standard method. However, XML variants are perhaps better suited to documenting the geographic component of UMN's because of their capabilities of providing a visualization of the metadata [e.g., geography markup language (GML) or keyhole markup language (KML); Open Geospatial Consortium 2012].

Overall, *dataset metadata* need to adhere to the relevant "schemas" for the chosen encoding method(s) that provide(s) the "structure" for describing digital geographic datasets (e.g., WMO Core Metadata Profile and the ISO19100 series, especially the ISO19115 geographical metadata standard and/or the ISO19136 GML metadata standard). These schemas explicitly define metadata elements and structures while establishing a common set of metadata terminology, definitions, and extension procedures for reporting. The network metadata directory (Table 8) includes the universal information required for inclusion in any of the aforementioned metadata-encoding mechanisms.

CONCLUSIONS. This first effort to create a standardized metadata protocol for UMNs draws upon recommendations from a range of sources to regularize UMN data (and improve compatibility with other nonmeteorological UMNs). The goal is to standardize UMN metadata based on best practices, personal experiences, and official recommendations. It is particularly clear that standardized terms, specific site classification techniques, and an urban network classification scheme would be of benefit to network implementers and end users alike. With implementations and discussion, the urban meteorological community will hopefully arrive at a consensus that is appropriate for current technologies, including more detailed requirements (e.g., variable-specific QA/QC procedures). The intent of this paper is to promote further discussions to facilitate this process.

Long-term, baseline datasets obtained from UMNs are required for a broad spectrum of applications, but the datasets need to be high quality and reliable in order to ensure accurate usage, thus furthering our understanding of increasingly important urban environments. It is acknowledged that it is difficult to ensure guidelines are universally adhered to (Stewart 2011); however, the publication of such protocols significantly increases the likelihood of adoption and is essential to further the understanding of the urban climate.

ACKNOWLEDGMENTS. This work is funded by the U.K. Natural Environmental Research Council (Research Grant NE/I006915/1), which is primarily funding the deployment of the HiTemp network, consisting of 250 wireless air temperature sensors and 25 weather stations across Birmingham, United Kingdom. This network is part of the wider urban meteorological research undertaken by the Birmingham Urban Climate Laboratory (www.bucl.org.uk). The authors would like to thank Prof. Tim Oke and Dr. Iain Stewart for their valuable comments during the preparation of this manuscript, in addition to delegates at ICUC-8, who provided valuable suggestions via formal (and informal) discussions during the "Urban Weather Networks" session when this protocol was first introduced (Muller et al. 2012). Finally, thank you to the anonymous reviewers for their comments, which were integrated into the manuscript.

REFERENCES

Aguilar, E., I. Auer, M. Brunet, T. C. Peterson, and J. Wieringa, 2003: Guidance on metadata and homogenization. WMO/TD-1186, WCDMP-53, 50 pp.

Basara, J. B., and Coauthors, 2010: The Oklahoma City Micronet. *Meteor. Appl.,* **18,** 252–261.

Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson, and M. D. Eilts, 1995: The Oklahoma Mesonet: A technical overview. *J. Atmos. Oceanic Technol.,* **12,** 5–19.

Brunt, J., B. Benson, J. Vande Castle, D. Henshaw, and J. Porter, Eds., 2007: LTER network cyberinfrastructure strategic plan—Version 4. Long Term Ecological Research Network, 31 pp. [Available online at http://intranet2.lternet.edu/sites/intranet2.lternet.edu/files/documents/LTER_History/Planning_Documents/LTER_CI_Strategic_Plan_4.pdf.]

Chandler, T., 1962: London's urban climate. *Geogr. J.,* **128,** 279–298.

Chapman, L., J. A. Azevedo, T. Prieto-Lopez, 2013: Urban heat and critical infrastructure networks: A viewpoint. *Urban Climate,* **3,** 7–12.

Davenport, A. G., C. S. B. Grimmond, T. R. Oke, and J. Wieringa, 2000: Estimating the roughness of cities and sheltered country. Preprints, *12th Conf. on Applied Climatology,* Asheville, NC, Amer. Meteor. Soc., 96–99.

Ellefsen, R., 1991: Mapping and measuring buildings in the canopy boundary layer in ten U.S. cities. *Energy Build.,* **16,** 1025–1049.

Estrin, D., W. Michener, and G. Bonito, 2003: Environmental cyberinfrastructure needs for distributed sensor networks: A report from a National Science Foundation sponsored workshop. Scripps

Institution of Oceanography, 65 pp. [Available online at https://intranet2.lternet.edu/sites/intranet2.lternet.edu/files/documents/Scientific_Reports/Cyberinfrastructure/cyberRforWeb.pdf.]

Fiebrich, C. A., C. R. Morgan, A. G. McCombs, P. K. Hall Jr., and R. A. McPherson, 2010: Quality assurance procedures for mesoscale meteorological data. *J. Atmos. Oceanic Technol.,* **27,** 1565–1582.

Gandin, L. S., 1970: The planning of meteorological station networks. Agricultural Meteorology Programme Tech. Note 111, WMO/TD-265, 35 pp.

Grimmond, C. S. B., 2006: Progress in measuring and observing the urban atmosphere. *Theor. Appl. Climatol.,* **84** (1–3), 3–22.

——, and T. R. Oke, 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J. Appl. Meteor.,* **38,** 1262–1292.

——, and Coauthors, 2010: Climate and more sustainable cities: Climate information for improved planning and management of cities (producers/capabilities perspective). *Procedia Environ. Sci.,* **1,** 247–274.

Hart, J. K., and K. Martinez, 2006: Environmental sensor networks: A revolution in the earth system science? *Earth Sci. Rev.,* **78** (3–4), 177–191.

Kidd, C., and L. Chapman, 2012: Derivation of sky view factors from lidar data. *Int. J. Remote Sens.,* **33,** 3640–3652.

Kljun, N., M. Rotach, and H. P. Schmid, 2002: A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications. *Bound.-Layer Meteor.,* **103,** 205–226.

Kolokotroni, M., I. Giannitsaris, and R. Watkins, 2006: The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. *Sol. Energy,* **80,** 393–392.

Koskinen, J. T., and Coauthors, 2011: The Helsinki Testbed: A mesoscale measurement, research, and service platform. *Bull. Amer. Meteor. Soc.,* **92,** 325–342.

Loridan, T., and C. S. B. Grimmond, 2012a: Characterization of energy flux partitioning in urban environments: Links with surface seasonal properties. *J. Appl. Meteor. Climatol.,* **51,** 219–241.

——, and ——, 2012b: Multi-site evaluation of an urban land-surface model: Intra-urban heterogeneity, seasonality and parameter complexity requirements. *Quart. J. Roy. Meteor. Soc.,* **138,** 1094–1113.

——, F. Lindberg, O. Jorba, S. Kotthaus, S. Grossman-Clarke, and C. S. B. Grimmond, 2013: High resolution simulation of the variability of surface energy balance fluxes across central London with urban zones for energy partitioning. *Bound.-Layer Meteor.,* in press, doi:10.1007/s10546-013-9797-y.

Manfredi, J., T. Walters, G. Wilke, L. Osnorne, R. Hart, T. Incrocci, and T. Schmitt, 2005: Road Weather Information System environmental sensor station siting guidelines. FHWA Publ. FHWA-HOP-05-026, 46 pp.

McGuirk, M., and E. May, 2003: USCRN metadata management—Survey to operations. NDCD Draft Rep., 14 pp. [Available online at http://www1.ncdc.noaa.gov/pub/data/uscrn/documentation/metadata/MetaDataMangt.doc.]

McPherson, R. A., and Coauthors, 2007: Statewide monitoring of the mesoscale environment: A technical update on the Oklahoma Mesonet. *J. Atmos. Oceanic Technol.,* **24,** 301–321.

Mikami, T., H. Ando, W. Morishima, T. Izumi, and T. Shioda, 2003: A new urban heat island monitoring system in Tokyo. *Proc. Fifth Int. Conf. on Urban Climate,* Lodz, Poland, International Association for Urban Climate, O.3.5. [Available online at http://nargeo.geo.uni.lodz.pl/~icuc5/text/O_3_5.pdf.]

Mizuno, M., Y. Nakamura, H. Murakami, and S. Yamamoto, 1990/1991: Effects of land use on urban horizontal atmospheric temperature distributions. *Energy Build.,* **15,** 165–176.

Muller, C. L., L. Chapman, D. T. Young, C. S. B. Grimmond, and X. Cai, 2012: Sensors and the city: Lessons learnt and a proposed protocol. *Proc. Int. Conf. on Urban Climatology 8,* Dublin, Ireland, International Association for Urban Climate, Abstract 54. [Available online at https://www.dropbox.com/sh/4x3vtvxg031mja4/GEUGIdcFoA/Proceedings_18Feb.pdf.]

——, ——, C. S. B. Grimmond, D. T. Young, and X. Cai, 2013: Sensors and the city: a review of urban meteorological networks. *Int. J. Climatol.,* **33,** 1585–1600, doi:10.1002/joc.3678.

NISO, 2004: Understanding metadata. National Information Standards Organization Press, 20 pp. [Available online at www.niso.org/publications/press/UnderstandingMetadata.pdf.]

NOAA, 2004: COOP modernization: Building the National Cooperative Mesonet program development plan. NOAA, 62 pp. [Available online at www.nws.noaa.gov/os/coop/reference/PDP4COOP.pdf.]

NRC, 2009: *Observing Weather and Climate from the Ground Up: A Nationwide Network and Networks.* National Academies Press, 250 pp.

——, 2012: *Urban Meteorology: Forecasting, Monitoring and Meeting Users' Needs.* National Academies Press, 176 pp.

Oke, T. R., 1982: The energetic basis of the urban heat island. *Quart. J. Roy. Meteor. Soc.,* **108,** 1–24.

——, 1984: Methods in urban climatology. *Applied Climatology: 25th International Geographical Congress*

Symposium 18; Applied Geography, W. Kirchhofer, A. Ohmura, and H. Wanner, Eds., Zurcher Geographische Schriften, Vol. 14, Geographisches Institut, 19–29.

——, 2004: Siting and exposure of meteorological instruments at urban sites. Tech. Rep. *27th NATO/CCMS Int. Technical Meeting on Air Pollution Modelling and its Application,* Banff, AB, Canada, University of Aveiro and University of Calgary, 14 pp. [Available online at http://urban-climate.com/ITM04-Oke.pdf.]

——, 2006a: Initial guidance to obtain representative meteorological observations at urban sites. Instruments and Observing Methods Rep. 81, WMO/TD-1250, 47 pp. [Available online at www.wmo.int/pages/prog/www/IMOP/publications/IOM-81/IOM-81-UrbanMetObs.pdf.]

——, 2006b: Towards better scientific communication in urban climate. *Theor. Appl. Climatol.,* **84** (1–3), 179–190.

——, 2009: The need to establish protocols in urban heat island work. *Eighth Symp. on the Urban Environment,* Phoenix, AZ, Amer. Meteor. Soc., J8.4. [Available online at https://ams.confex.com/ams/89annual/techprogram/paper_150552.htm.]

Open Geospatial Consortium, cited 2012: OGC standards and supporting documents. [Available online at www.opengeospatial.org/standards/.]

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.,* **56,** 527–530.

Poutiainen, J., E. Saltikoff, W. F. Dabberdt, J. Koistinen, and H. Turtiainen, 2006: Helsinki Testbed: A new open facility to test instrumentation technology for atmospheric measurements. *Extended Abstracts, WMO Technical Conf. on Meteorological and Environmental Instruments and Methods of Observation,* Geneva, Switzerland, World Meteorological Society, Instruments and Observing Methods Rep. 94, WMO/TD-1354, 13 pp. [Available online at www.wmo.int/pages/prog/www/IMOP/publications/IOM-94-TECO2006/1(2)_Poutiainen_Finland.pdf.]

Robinson, P., 2010: The London Meteorological Monitoring Network. M.S. thesis, Department of Geography, King's College London, 356 pp.

Roth, M., 2000: Review of atmospheric turbulence over cities. *Quart. J. Roy. Meteor. Soc.,* **126,** 941–990.

Runnalls, K. E., and T. R. Oke, 2006: A technique to detect microclimate inhomogeneities in historical records of screen-level air temperature. *J. Climate,* **19,** 959–978.

Schmid, H. P., 2002: Footprint modeling for vegetation atmosphere exchange studies: A review and perspective. *Agric. For. Meteor.,* **113,** 159–183.

Schroeder, A. J., J. B. Basara, and B. G. Illston, 2010: Challenges associated with classifying urban meteorological stations: The Oklahoma City Micronet example. *Open Atmos. Sci. J.,* **4,** 88–100.

Schroeder, J. L., W. S. Burgett, K. B. Haynie, I. Sonmez, G. D. Skwira, A. L. Doggett, and J. W. Lipe, 2005: The West Texas Mesonet: A technical overview. *J. Atmos. Oceanic Technol.,* **22,** 211–222.

Shafer, M. A., C. A. Fiebrich, D. S. Arndt, S. E. Fredrickson, and T. W. Hughes, 2000: Quality assurance procedures in the Oklahoma Mesonetwork. *J. Atmos. Oceanic Technol.,* **17,** 474–494.

Stewart, I. D., 2011: A systematic review and scientific critique of methodology in modern urban heat island literature. *Int. J. Climatol.,* **31,** 200–217.

——, and T. R. Oke, 2009: Newly developed "thermal climate zones" for defining and measuring heat island magnitude in the canopy layer. Preprints, *T. R. Oke Symp. and Eighth Symp. on the Urban Environment,* Phoenix, AZ, Amer. Meteor. Soc., J8.2A. [Available online at https://ams.confex.com/ams/pdfpapers/150476.pdf.]

——, and ——, 2012: Local climate zones for urban temperature studies. *Bull. Amer. Meteor. Soc.,* **93,** 1879–1900.

Tanner, C. B., 1963: *Basic Instrumentation and Measurements for Plant Environment and Micrometeorology.* in Soils Bulletin, Vol. 6, University of Wisconsin—Madison.

Tseng, C. C., and N. B. Chang, 2001: Assessing relocation strategy of urban air quality monitoring network by compromise programming. *Environ. Int.,* **26,** 524–541.

Wanner, H., and P. Fillinger, 1989: Orographical influence on urban climate. *Wea. Climate,* **9,** 22–28.

WMO, 2003: GCOS Climate Monitoring Principles [Available online at www.wmo.int/pages/prog/gcos/documents/GCOS_Climate_Monitoring_Principles.pdf.]

——, 2008: Guide to meteorological instruments and methods of observation. 7th ed. WMO-8. [Available online at www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf.]

——, 2011: Guide to climatological practices. WMO-100. [Available online at www.wmo.int/pages/prog/wcp/ccl/documents/WMO_100_en.pdf.]